Statistical physics concepts and network science metrics to study agent interactions in the Agrotechnological Districts of the Semear Digital Center

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Abstract

This study aims to understand the underlying structural drivers of interactions between producers and markets — such as traceability, certification, and quality control — using tools from network science and statistical physics. While direct data on producers is not yet available, we use scientific coauthorship networks from Embrapa (BDPA) as a proxy to explore evolving agent interactions such as collaboration, competition, etc. By projecting bipartite networks and analyzing them over cumulative time windows, we investigate the formation of associations, the growth of connected components, and indicators of institutional cohesion. Metrics like modularity, assortativity, and the emergence of a giant component are discussed in the light of concepts such as entropy, Hamiltonians, and phase transitions. The study proposes that these frameworks can be extended to model real-world producer networks, guiding public policy and institutional planning with a focus on smallholders.

Keywords: Network Science; Statistical Physics; Coauthorship Networks; Producer-Market Interactions; Traceability; Certification.

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1. Introduction

The increasing complexity of relationships between rural producers, public institutions, and the market calls for new approaches to understand the forces shaping such interactions. Requirements such as traceability, origin certification, quality control, and institutional compliance create both pressure and incentives for agents to organize in cooperative and interconnected ways. Theoretical and empirical advances in the modeling of agricultural trade networks show that social evolutionary processes and peer effects play a central role in shaping market outcomes (Kopp; Salecker, 2020). Additionally, agent-based network approaches have proven essential for analyzing how rural producer organizations emerge and sustain themselves under institutional and environmental constraints (Latyskiy; Berger, 2012).

This study aims to explore how quantitative indicators from network science and principles from statistical physics can help identify structural patterns in rural agent interactions. As a proxy data, while an in-depth questionnaire has not been applied in the ten Agro-Technological Districts of the Semear Center, we analyze the scientific network of Embrapa's BDPA (Brazilian Agricultural Research Database) (Bergier et al., 2021), applying bipartite and projected network analysis across time (Blondel et al., 2008; Lambiotte et al., 2004).

2. Theoretical Hypothesis

Drawing from statistical physics, we hypothesize that interaction networks tend toward configurations that minimize a system-wide energy function, akin to a Hamiltonian. In this framework, a Hamiltonian represents the systemic "cost" of a given network configuration: fragmented and poorly modular networks correspond to high-energy, inefficient structures, while cohesive and modular networks represent low-energy, cooperative states. This conceptual approach echoes current studies on phase transitions and cooperative behavior in complex networks (Gao et al., 2024).

3. Methodology and Network Construction

The Gephi platform was employed to generate visualizations (Figure 1) and will be used to extract key network metrics as potential indicators. Modularity and the number of communities were measured with Gephi; other metrics such as average degree, path length, community structure, and assortativity will also be calculated. This will allow a detailed temporal comparison of network growth and internal reorganization using both topological and statistical indicators.

4. Preliminary Results

The cumulative projected network (1971–2024) reveals structural features characteristic of complex scientific collaboration systems. As a preliminary result, both the bipartite network (Authors × Titles) and the projected author-author coauthorship network were generated for the full period under analysis.

Notably, the author-author projection exhibits high modularity (0.788), along with the detection of 10,779 distinct communities. This indicates a strongly modular topology in which collaboration tends to occur within densely connected clusters. Figure 1A shows the bipartite network structure filtered for the year 2024 while Figure 1B presents the corresponding author–author network for the same year.

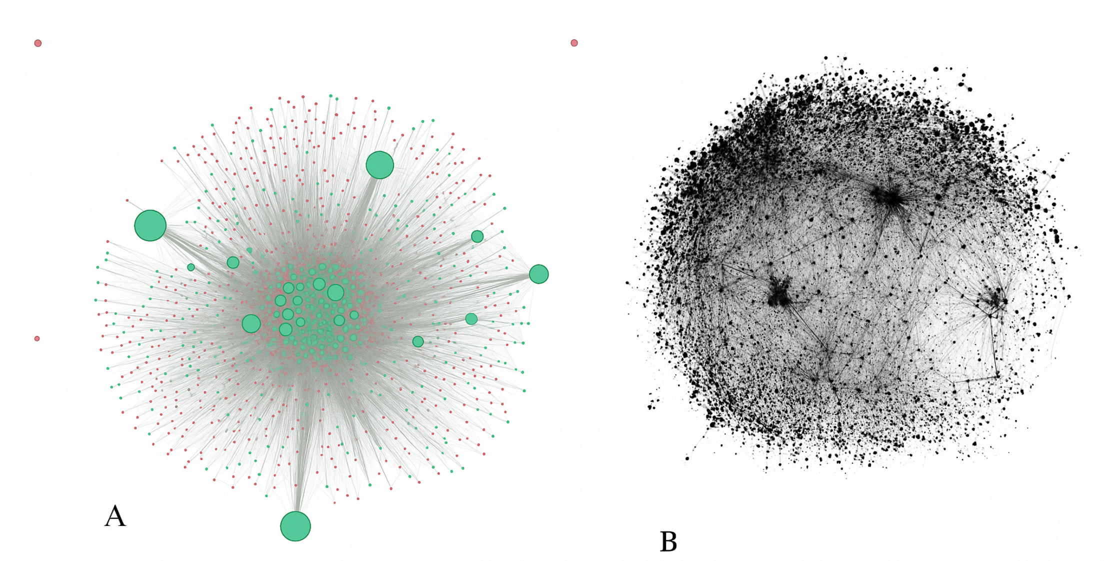

Figure 1. Bipartite and coauthorship networks: (A) Bipartite network visualization (Authors × Titles) for the year 2024. Green nodes represent publications; pink nodes represent authors. Node size is proportional to degree: larger publication nodes indicate papers with more coauthors, while larger author nodes indicate individuals with more contributions. The layout highlights the structure of collaborations around highly connected nodes; (B) Coauthorship network projection for the year 2024. Each node represents an individual author, and edges represent coauthorships derived from joint publications.

The data-driven construction of the network reveals structural transformations over time, reflecting shifts in collaboration patterns and the emergence of new communities — consistent with findings from recent studies on the evolution of complex scientific systems (Bergier et al., 2021; Gao; Yan, 2023).

5. Applications to Producer Networks

The observed network behaviors can be translated into insights relevant for real-world producer networks. For instance, the emergence of associations or cooperatives might be associated with the appearance of modular substructures and increasing community count (Latyskiy; Berger, 2012). Moreover, traceability and quality control can be related topersistent connectivity and high centrality hubs. And policy and market shocks may often be mirrored by shifts in network topology, such as fragmentation or realignment.

Alternatively, evidence suggests that individual decision-making is shaped by peer dynamics and localized influence within networks (Kopp; Salecker, 2020). These peer effects may explain the spontaneous formation of productive clusters and also highlight vulnerabilities to disconnection or systemic inefficiencies.

6. Conclusion

This work illustrates that concepts from statistical physics and indicators from network science can be applied to understand the evolving structure as a response to the digital transformation of medium and small rural producers. The analysis of scientific coauthorship networks allows us to simulate and interpret dynamic metrics and indicators such as modularity, entropy, and cooperation level that will be further applied to the data obtained from the Agro-Technological Districts questionnaires. The analysis already conducted on Embrapa's coauthorship networks demonstrates the robustness of this approach and opens pathways for further empirical exploration.

7. Future Perspectives

This study contributes to the growing literature that combines network science with statistical physics. Future directions include:

1) Entropy-based analyses by using Shannon entropy to quantify uncertainty and structural diversity within the networks.

2) Phase transitions via modeling how small changes in connectivity parameters lead to abrupt structural reorganizations.

3) Level curves of the fraction of nodes in the giant component, as a function of time (years) and average degree, to detect critical surfaces by mapping thresholds beyond which cooperation emerges or collapses.

4) Test Hamiltonians as systemic cost functions to evaluate equilibrium or "optimized" collaboration states.

5) Bifurcation diagrams to capture abrupt regime shifts (e.g., in modularity or assortativity).

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